Contents list available at JESE website

Journal of Emerging Science and Engineering

Journal homepage: https://journal.cbiore.id/index.php/jese

Review Article

Biomass resources and thermal conversion biomass to biofuel for cleaner energy: A review

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Abstract. Biofuel is considered as one of the solutions to future energy problems. Unlike fossil fuels, biofuel is a renewable fuel source produced from biomass. Biomass comes from a wide variety of plants and animals and even waste. Therefore, the production of biofuel from biomass is promising not only to solve energy problems but also to solve other social problems. This study will present some of the most potential biomass sources and thermal conversion processes of biomass for biofuel production.

Keywords: biomass resources, thermal conversion, combustion, pyrolysis, gasification

Received: xxx; Revised: xxxx; Accepted: xxx; Available online: xxx

1. Introduction

Biofuel has been attracting the attention of researchers for a long time and has been shown to be able to effectively replace fossil fuel sources, therefore, the research to find ways to produce biofuel efficiently on a large scale to gradually replace challenging fossil fuels is also of great interest. Biofuel sources can be obtained through the processing of biomass. There are three ways to convert biomass to biofuel including: Thermal conversion, biological conversion and mechanical conversion (T. Bridgwater, 2006). Depending on the desired finished product, the available raw materials and the facilities of the manufacturing plants, the methods of converting biomass into biofuel are selected specifically. Understanding how it works, the advantages and disadvantages of each method will create a basis for manufacturers to choose the most suitable method, helping the production of biofuels achieve maximum efficiency in both quality and quantity. Being able to produce high-quality biofuels in large quantities will make it easier and smoother to gradually replace fossil fuels with these fuels. This study only focuses on reviewing the latest findings of the method of biomass thermal conversion into biofuel. The article is divided into 4 parts: the first part is an introduction, the second part will introduce popular and potential biomass sources, the next part will present the methods of biomass thermal conversion to biofuel and the last part is conclusion.

2. Potential Biomass Resources

In fact, the biomass sources that can be converted into biofuel are extremely diverse, however, it is not so easy to choose the suitable biomass source. Figure 1 shows the most three important criteria for a potential source of biomass. With the below criteria, the most suitable and potential biomass sources include products of industrial crops; agricultural, forestry and fishery by-products and waste products; wastes from human activities.

Industrial crops are crops that usually cannot be consumed immediately after harvest, but must undergo industrial processing steps before final use, therefore, industrial crops are one of the most suitable sources of biomass. Industrial crops are capable of cyclically providing a large number of raw materials for biofuel production from biomass. In recent years, a lot of biofuels derived from industrial crops have attracted special attention from researchers. In 2019, Hoang and Pham in a study compared the performance, emission characteristics, deposit formation, and lubricating oil degradation of engines when using straight Jatropha oil preheated at 90°C (SJO90) and normal diesel fuel (DF) (Hoang & Pham, 2018). Research results show that specific fuel consumption for SJO90 increased by 10.65% compared to DF, emissions including unburnt hydrocarbons (UHC) and CO increased by 11.52% and 17.94% respectively while NO_x emissions decreased by 6.59%. In another study, a blend of Mahua biodiesel and diesel with Al_2O_3 particles additives also gave positive results when the above fuel mixture tended to have enhanced brake thermal efficiency (BTE) and reduced brake specific fuel consumption (BSFC). Emission indicators also improved when most important indicators such as CO, HC and NO_x emissions decreased, only CO_2 emissions increased (Mohan Chandra Kumar & Simhadri, 2022).

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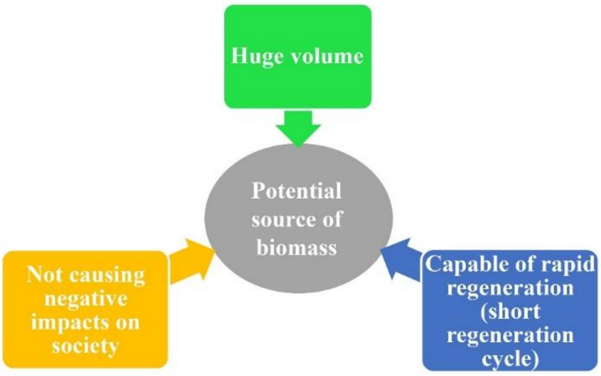


Figure 1. Criteria of potential source of biomass

An extremely suitable source of biomass that has many similarities with products of industrial crops is agricultural, forestry and fishery by-products and waste products. **Figure 2** shows an ideal approach to agro-forestry-fishery by- products and waste products to help complete the economic circle. Because it is directly related to farming and breeding activities, this source of biomass is also large in number and cyclical. Moreover, instead of wastefully discarding these by-products and wastes, factories can fully utilize these products as input materials for energy production. Biodiesel derived from rice bran oil has been shown to be suitable as an alternative fuel source for fossil fuel sources (Hoang, Tabatabaei, et al., 2021). The results of the study show that the ratio of 20% rice bran oil and 80% petro-diesel will create a fuel mixture that can still ensure the performance and combustion characteristics of the engine but can significantly reduce emissions. Rice straw is also a common agricultural by-product and has also been shown to be suitable for biofuel production (Sharma et al., 2020). Most studies show that biodiesel from agricultural, forestry and fishery by-products and waste sources is suitable for mixing with fossil fuels to improve some engine characteristics, but not to completely replace them. However, this still helps to partly reduce the consumption of traditional fuels besides being able to make full use of all agro-forestry-fishery products.

Municipal solid waste (MSW) is another extremely suitable source of biomass. **Figure 3** shows the contribution rates of different types of municipal solid waste (*National Overview: Facts and Figures on Materials, Wastes and Recycling | US EPA*, n.d.). It is very clear that human activities generate an extremely huge amount of waste, and despite the increasing attention and improvement of recycling and reuse technologies, a large amount of waste has not yet been treated appropriately. This amount of waste will normally be destroyed or worse, illegally discharged into the environment. Fortunately, recent studies show that Municipal solid waste can become an extremely potential source of biomass. Anh Tuan Hoang et. al. analyzed the characteristics, management strategy, and role in circular economy of Municipal Solid Waste-to-energy methods (Hoang et al., 2022). In a separate study, E.M. Barampouti et. al. also points out the barriers and opportunities of producing liquid biofuels from the organic fraction of municipal solid waste (Barampouti et al., 2019). In general, the use of municipal solid waste as a raw material for biofuel production is not only significant in terms of energy solutions, but also in terms of waste management.

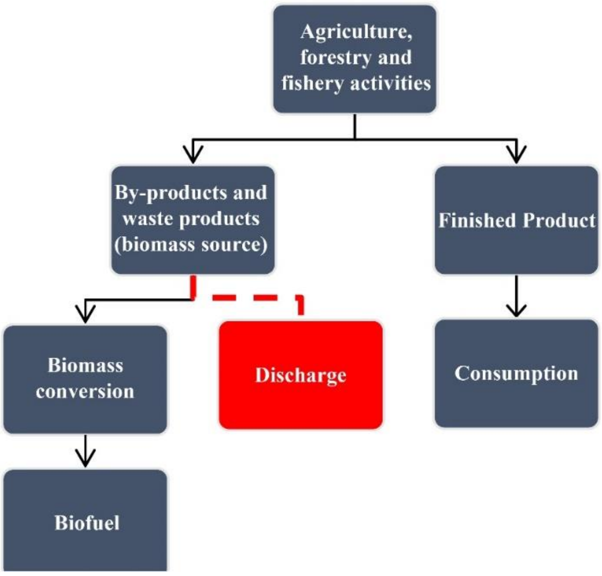


Figure 2. Optimal approach for agro-forestry-fishery activities

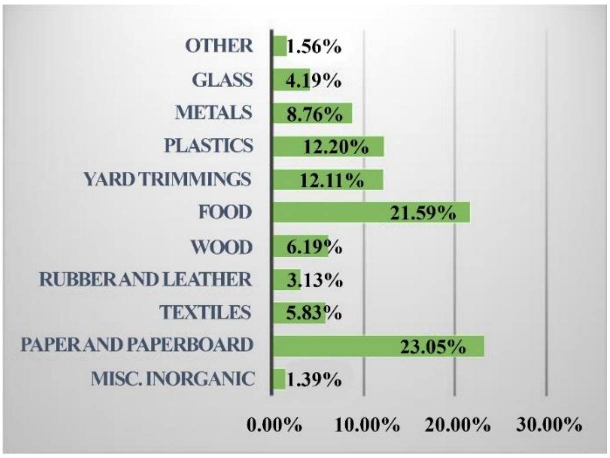


Figure 3. The contribution rates of different types of municipal solid waste (National Overview: Facts and Figures on Materials, Wastes and Recycling | US EPA, n.d.)

3. Biomass Thermal Conversion

Figure 4 shows biomass conversion methods and their products. As mentioned in the previous part, thermal conversion, biological conversion and mechanical conversion are three ways of biomass conversion to create biofuel. For each, there are many different methods to proceed depending on the input materials, the actual conditions and the desired output. Understanding the biomass conversion methods and their advantages and disadvantages is necessary to help managers and businesses have the right approach to avoid wasting available resources.

There are 3 main methods to convert biomass to biofuel by thermal conversion including pyrolysis, gasification and combustion. Usually, to achieve the highest efficiency, the above methods are rarely applied alone, but will be combined with many different methods. Each method has its own advantages and disadvantages, and the combination will help overcome the disadvantages of each method and maximize their advantages. Within the framework of this study, we only focus on thermal conversion biodiesel.

3.1. Combustion

Combustion is one of the simplest methods of thermal conversion, as opposed to pyrolysis and gasification. Biomass can provide energy in the form of heat simply by burning it. The amount of heat obtained is more or less depending on the characteristics and quantity of biomass as well as the combustion method. In most industrialized and emerging nations, combustion is already a well-established commercial technology with wide applications. Current research on improving combustion techniques has mostly focused on minimizing the negative effects this process can have. There are three basic types of combustion: grate-firing, pulverized fuel and fluidized bed (Rosendahl, n.d.). The most popular of them is grate firing. This technique involves placing biomass on a grate and progressively transferring material via holes in the grate. This method is best suited for coarse and irregular particle sizes. The advantage of this method is that the plant type is flexible and relatively simple, however, having to transport biomass over large distances consumes a lot of energy and directly increases costs. Besides, the emission factor is also a concern when applying this technique in large quantities for a long time. Therefore, on large scales, biomass will often be burned by a pulverized fuel process. The biomass is burned after being processed into a powder. However, employing biomass in pulverized fuel boilers also has problems, especially the greater combustion temperature leads to corrosion and slagging issues.

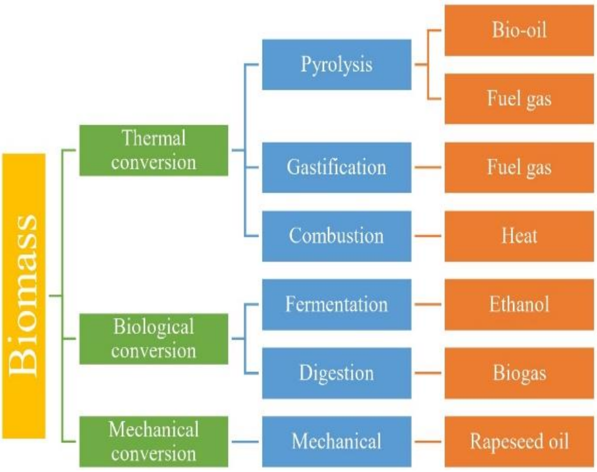


Figure 4. Biomass conversion methods and their products

As a result, biomass is frequently burned in combination with coal since coal's chemical characteristics help to offset the problems caused by biomass's high chloride level. Another problem with this technique is that the biomass must be dry in order for this procedure to work, so this method also consumes a lot of energy for drying and grinding. A more recent combustion technique called fluidized beds is suggested to address the aforementioned drawbacks. Plants are more efficient and emit less pollutants. In a mixture with incoming air, the biomass was combined with a medium (often sand). The process may thus be utilized with somewhat coarse and moist material since the warmth in the bed partially gasifies the biomass. This approach is less common because of the setup's relative complexity and the challenges associated with operating a plant with a component load, not suitable for available facilities. However, since fluidized beds may reach a higher level of fuel flexibility than pulverized fuel, all huge new biomass facilities are anticipated to be of this kind.

3.2. Pyrolysis

Dehydration, isomerization, dehydrogenation, aromatization, charring, oxidation, and other processes coexist throughout the complicated process of biomass pyrolysis. These are accompanied by secondary processes, such as cracking, syngas synthesis, condensation reactions, thermal degradation of water into water gas, etc. Initial conditions setup especially temperature and growth rate will directly affect the final product rate of the process. Accordingly, the common output products are usually steam, hydrogen, coal, tar, aliphatic and aromatic hydrocarbons, carbon oxides, polymers (Lewandowski et al., 2020). Pyrolysis is generally classified into 3 types of slow, fast and flash pyrolysis based on their process characteristics. **Table 1** shows the differences between the three types of pyrolysis (Balat et al., 2009). Among them, slow pyrolysis is a rudimentary method and has many disadvantages that are not suitable for an industrial scale, so in the framework of this study, we will not analyze it in depth.

Biomass is swiftly heated to a high temperature without oxygen as part of the fast pyrolysis process. Depending on the feedstock utilized, rapid pyrolysis typically yields 10%–20% of gaseous phase, 15%–25% of solids (mostly charcoal), and the rest are oily products, accounting for 60-75% on a weight basis. Biomass is typically converted into liquids under conditions of low temperature, rapid heating, and brief residence time. The fundamental elements of the fast pyrolysis process include quick cooling of vapours and aerosols for high bio-oil production, high heat transfer and heating rates, and precise temperature control of the reaction (Demirbaş & Arin, 2010). A variety of specialty and commodity chemicals, as well as liquid fuels, are produced using fast-pyrolysis technology. The processing of solid biomass and usage are separated by the ease and affordability with which this liquid product can be transported and stored (Brammer et al., 2006). Additionally, it has the ability to produce a variety of priceless compounds that are far more desirable than fuels due to their great added value. Low initial investment costs, high energy efficiency at small scale are outstanding advantages of fast pyrolysis techniques compared to other technologies.

Flash pyrolysis is another potential method for converting biomass into solid, liquid, and gaseous fuels that can yield up to 75% more bio-oil is (Demirbas, 2000). The salient features that distinguish flash pyrolysis from other pyrolysis methods can be mentioned as the evaporation and heating of the particles taking place at a high rate in an inert atmosphere, the ideal temperature of the process is about 450°C to 1000°C and exceptionally short gas residence time of less than 1 second (Aguado et al., 2002). However, this method has certain technological drawbacks, such as the oil's low thermal stability, corrosiveness, and presence of particulates. The char's catalytic action causes a gradual increase in viscosity, alkali in the char dissolves into the oil, and pyrolytic water is produced. More research is needed to overcome the disadvantages of flash pyrolysis and exploit its full potential.

Pyrolysis is an environmentally sensitive process; any small change can have a significant impact on process performance. Temperature in particular is crucial for pyrolysis because it supplies the energy needed to break the chemical interactions between the various biomass components. Normally, the liquid yield of the pyrolysis process will benefit from an increase in temperature., however, too high a temperature will conversely affect the yield of the final product. The above phenomenon has been proved by Jung et al. (Jung et al., 2008). During the experiment, authors conduct pyrolysis sawdust by applying a fluidized bed reactor. When the temperature increases from 350 to 450°C, bio-oil yield also increases from 56 to 72 wt%. However, when the temperature continued to increase to 510°C, the bio-oil production decreased to only 61 wt%. The same goes for rice straw pyrolysis where the optimum temperature fluctuates only around 445°C. Increasing the temperature not only does not increase yield but even decreases. In another study, Tsai et al. proved that 400 to 500°C is the ideal temperature for rice husk pyrolysis. In another separate study, the same was confirmed by Lazzari et al. when 450-600°C is the most suitable condition for mango seed almond pyrolysis. It can be concluded that, according to the findings of various research, the best temperature range for the creation of liquid yield is between 300 and 550 °C. **Table 2** shows some optimal temperatures for pyrolysis of different biomass.

Table 1. Typical operating conditions of different pyrolysis process (Balat et al., 2009)

Pyrolysis process	Solid residence time (s)	Heating rate (K/s)	Particle size (mm)	Temp. (K)
Slow	450-550	0.1-1	5-50	550-950
Fast	0.5-10	10-200	<1	850-1250
Flash	<0.5	>1000	<0.2	1050-1300

Table 2. Typical operating conditions of different pyrolysis process (Balat et al., 2009)

Biomass	Optimal Temperature (°C)	Liquid yield	Ref
Rice husk	400-500	35.92%	(Tsai et al., 2007)
Mango seed almond	650	38.8%	(Lazzari et al., 2016)
Neem de-oiled cake	400	40.2%	(Volli & Singh, 2012)
Cynara cardunculus L.	400	56.23%	(Encinar et al., 2000)
Olive bagasse	600	72.4%	(Encinar et al., 2000)
Rice husk	450	70%	(Alvarez et al., 2014)
Poplar	455	69%	(Makibar et al., 2015)
Cassava stalk	469	61.39%	(Pattiya & Suttibak, 2012)
Cassava rhizome	472	63.23%	(Pattiya & Suttibak, 2012)
Sugarcane bagasse	475	56%	(Islam et al., 2010)
Jatropha seed shell cake	470	48%	(Kim et al., 2013)
Residues from palm tree	500	72.4%	(Abdullah & Gerhauser, 2008)

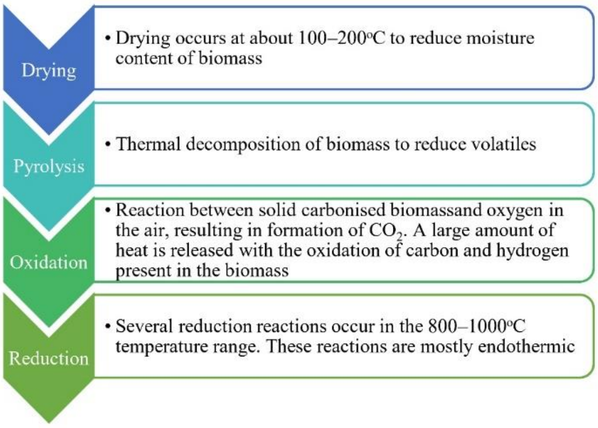
Heating rate is also a factor that profoundly affects the pyrolysis process. During rapid pyrolysis, a higher heating rate can reduce the contact time between the biomass and the high temperature as well as limit the discontinuity and delay between primary and subordinate cracking. As a result, the combination of a faster vapor condensation rate and a higher heating rate prevents subordinate cracking and encourages the formation of light composite and aromatics (SHAFIZADEH & CHIN, 1977; Xiong et al., 2018). However, a similar phenomenon with temperature also occurs at the heating rate where each different type of biomass will accommodate different heating rates. Once the optimal heating rate has been reached, further increasing this parameter does not make much sense and can even backfire in many cases. Onay et al. evaluated the effect of heating rates using a fixed bed reactor to pyrolysis rapeseed under three separated heating rates of 100, 300, and 800°C/min and compared bio-oil yields. Experimental results show that when the heating rate is increased from 100 to 300°C/min, the output of bio-oil rises dramatically by around 58%. When the heating rate exceeded 300°C/min, bio-oil yields speed is the lowest (Onay et al., 2001). Similarly, rice husk pyrolysis was studied by Tsai et al. (Tsai et al., 2007) using a range of heating speeds from 100 to 500°C /min. The oil yield was most attained at 200°C /min and then in a steady state even if the heating rate increases further.

Residence time is also a key factor affecting pyrolysis and an essential element for detailing the procedures for developing pyrolysis reactors. In theory, longer residence times support the secondary cracking of vapors causes a rise in the number of tiny char particles accumulating in the hot filter, transfer line, and reactor. The porous structure in combination with the metal appearance in the char particles further promotes the secondary reactions that reduce the liquid yield. Islam et al studied the influence of residence by applying a fixed bed reactor to perform pyrolysis sugarcane bagasse. The results of the study show that the gas yield is increased with increasing residence time from 5 to 20s, however, in the opposite direction, bio-oil and biochar yield is decreased.

In addition, all the initial conditions of pyrolysis have an influence on the process including particle size, pressure, characteristics of biomass, reactor type, etc. In general, pyrolysis is a complex process with a wide variety of possible inputs, desired output products and different setup conditions. The effect of the initial conditions on the effectiveness of pyrolysis has been the subject of extensive investigation in recent years. As a result, factors such as temperature, heating rate, pressure, residence duration, and the quality and content of the biomass feedstock have the most significant impact on the final biofuel production's yield distribution as well as their physio-chemical characteristics (Hoang, Ong, et al., 2021).

3.3. Gasification

Gasification is the thermochemical conversion of carbonaceous material into syngas, which results in a high proportion of gaseous products (CO2, water, carbon monoxide, hydrogen and gaseous hydrocarbons), small quantities of char (solid product), ash, and condensable compounds (tars and oils). As an oxidizing agent, steam, air, or oxygen is added to the process. The quality of the gas generated may be controlled, and it is simpler and more adaptable to employ than the original biomass (e.g., it can be used to power gas engines and gas turbines or as a chemical feedstock for the production of liquid fuels). By transforming low- or negative-value feedstock into marketable fuels and goods, gasification adds value to the source material (Puig-Arnavat et al., 2010). Figure 5 shows the common gasification process.



- Drying occurs at about 100–200°C to reduce moisture content of biomass
- Thermal decomposition of biomass to reduce volatiles
- Reaction between solid carbonised biomassand oxygen in the air, resulting in formation of CO_2. A large amount of heat is released with the oxidation of carbon and hydrogen present in the biomass
- Several reduction reactions occur in the 800–1000°C temperature range. These reactions are mostly endothermic

Figure 5. The common gasification processes

Table 3. Gasification technologies and their product quality

Gasifier technologies	Gas composition, dry, vol%					Higher heating value (MJ N-1 m3)	Gas quality	
	H_2	CO	CO_2	CH_4	N_2		*Tars*	*Dust*
Fluid bed air-blown	9.1	14.2	19.7	6.9	50.1	5.4	Medium	Low
Updraft air-blown	11.4	23.2	9.5	3.1	52.8	5.5	Low	High
Downdraft air-blown	16.8	21.4	12.5	1.7	47.6	5.7	Low	Medium
Downdraft oxygen	31.2	48.1	15.2	2.3	3.2	10.4	High	High
Twin fluid bed	31.4	47.3	0	21.3	0	17.4	Medium	Low
Pyrolysis for comparison	40.8	19.7	18.2	21.1	1.2	13.3	Low	High

Similar to pyrolysis, conditions for gasification such as temperature, equivalent ratio, and pressure, have an impact on the composition of syngas (El-Emam et al., 2012). Table 3 shows gasification technologies and their product quality (A. V. Bridgwater, 1995).4565.

Theoretically, the higher the hydrogen content of fuel, the lower the vaporization temperature and the higher the probability of the fuel being in a gaseous state. This makes it easier for the fuel to mix with the air when used in an internal combustion engine, helping the fuel to burn cleaner and the engine's performance to be improved. Gasification or pyrolysis will increase directly or indirectly the relative hydrogen content (H/C ratio). Normally, oxygen will include about 40% content of biomass by mass, however, gasification will remove part of oxygen in biomass and produce a more energy dense product (Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory - Prabir Basu, n.d.). However, one issue to be aware of with gasification products is that gas is very expensive to store or transport compared to other products. Therefore, besides improving the efficiency of the gasification process, an efficient supply chain also needs to be designed to transport and use the finished product

4. Conclusion

Biofuel has been considered a suitable and potential alternative fuel source for the future. However, the current level of biofuel uses and efficiency is still low. The reason for this is partly due to the lack of popularity and inefficiencies in converting biomass to biofuel. In addition, the selection of biomass sources for biodiesel production without a reasonable approach can cause negative impacts to society such as pollution and ecological imbalance or indirectly affecting food supply. The most promising biomass sources should be biomass sources that can complete or supplement the chain of essential or indispensable activities in daily life, especially the reuse of by-products and waste products in agricultural, forestry and fishery activities or domestic waste. With the above modern approach, biofuel not only helps solve part of the energy problem, but also reduces other important social problems.

Besides finding the suitable biomass source, the stages of converting biomass into biofuel are also extremely important. Typically, the processes that convert biomass to biofuel are extremely sensitive to the conditions before and during execution. With industrial scale production, any small improvement in the process can help businesses reap huge profits as well as increase competitiveness in the market. Within the framework of the study, the potential biomass feedstock as well as the thermal conversion of biomass into biofuel were reviewed. Research is the basis for method selection as well as a premise to improve biofuel production activities to be smoother and more efficient. Future research directions should focus on how to effectively combine many conversion methods, as well as evaluate suitable catalysts that can be used to optimize biomass thermal conversion.

Acknowledgement

The authors would like to thank Van Lang University, Vietnam for funding this work.

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